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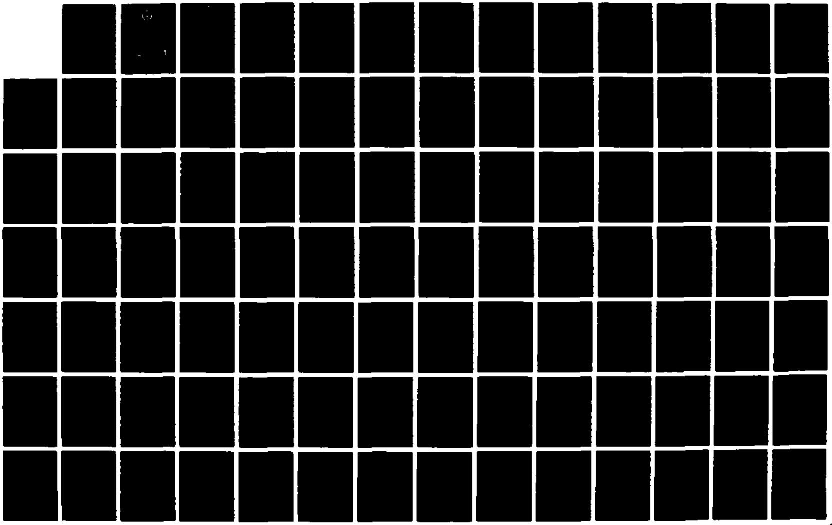

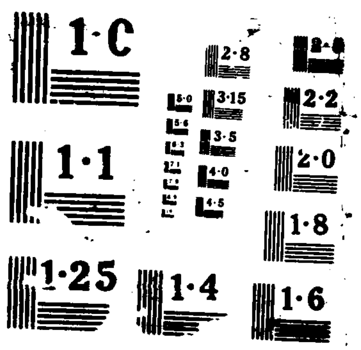
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THE DEPARTMENT OF DEFENSE

SUPERCONDUCTIVITY RESEARCH AND DEVELOPMENT OPTIONS

JULY 1987

A STUDY OF POSSIBLE DIRECTIONS FOR EXPLOITATION OF SUPERCONDUCTIVITY IN MILITARY APPLICATIONS

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

AD-A189 747

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: NONE
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: DoD Superconductivity Research & Development Working Group; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): DUSD (R&AT/RLM), 3E114 Pentagon, Washington, DC 20301-3082	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) DEPARTMENT OF DEFENSE SUPERCONDUCTIVITY RESEARCH AND DEVELOPMENT (DSRD) OPTIONS

12. PERSONAL AUTHOR(S)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ____ TO ____	1987 July	125

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
*Superconductivity, Superconducting, HTS(High Temperature Superconductivity), Research, Research management, Department of Defense, Military applications

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Although the technology associated with traditional low temperature superconductivity (LTS) materials is relatively mature, the scientific foundations for the newly discovered high temperature superconducting (HTS) materials are in a more rudimentary state, and the engineering parameters required for definition of possible realms of exploration are largely unknown. Within the limitations imposed by these unknown factors, this document sets forth a menu for a five-year Department of Defense Superconductivity Research and Development (DSRD) program. The goal of this program is to assure that the potential of HTS is realized at the earliest opportunity for military applications, including both small-and large-scale applications. Included in the study are (a) mention of the accomplishments and extensive program management experience of DoD in both the science and military applications of superconductivity and of ceramics, (b) an exposition of the rationale for the scope of DSRD, (c) several sections describing research, development, and demonstration projects which would be included in DSRD (including in each case the proposed

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
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DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Block 19, continued
additional level of effort above and beyond existing relevant program activity and funding) and (d) an overall summary of DSRD budget requirements. It is important to emphasize that DSRD will seek to integrate the scientific and technical capabilities of academic, industrial, and government laboratories in this endeavor and is pledged to close cooperative coordination with other superconductivity R&D activities, both federal and private. In fact, the program outlined here must be viewed as only a first iteration, one which must be further shaped and adjusted so that it will join with programs of other federal agencies into an integrated federal program.

DEPARTMENT OF DEFENSE SUPERCONDUCTIVITY RESEARCH AND DEVELOPMENT (DSRD) OPTIONS

A STUDY OF POSSIBLE DIRECTIONS FOR EXPLOITATION OF SUPERCONDUCTIVITY IN MILITARY APPLICATIONS

JULY 1987

DEPARTMENT OF DEFENSE SUPERCONDUCTIVITY RESEARCH AND DEVELOPMENT (DSRD) OPTIONS

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DEPARTMENT OF DEFENSE SUPERCONDUCTIVITY RESEARCH AND DEVELOPMENT (DSRD) OPTIONS

I. INTRODUCTION

The technology associated with traditional low temperature superconductivity (LTS) materials is relatively mature. More than 1000 LTS supermagnets, each large enough to encircle a human patient, are now in routine use world-wide in lifesaving magnetic resonance medical imaging systems. Another 1000 superconducting magnets, each 21 feet long, provide the particle beam bending capability for the world's largest machine, the Fermilab Tevatron particle accelerator. Development of LTS rotating electrical machines of unprecedented efficiency and power density is highly advanced. An experimental train, which holds the world's speed record (more than 300 MPH), utilizes LTS magnets which allow it to levitate above its tracks. LTS sensors (the most sensitive known) are in widespread use in scientific, technical, medical, and defense applications. Less mature, but highly impressive nonetheless, is the technology of LTS electronics (the world's fastest). The scientific underpinnings of these technology areas are for the most part well understood, and the myriad engineering parameters which define the limits of their use are well known.

In contrast, for the newly discovered high temperature superconducting (HTS) materials the scientific underpinnings are in a very rudimentary state, and the engineering parameters required for definition of possible realms of exploitation are largely unknown. Accordingly, prognostications on ultimate pay-off are risky at best, and any program plan, such as outlined here, is subject to great uncertainty. Although this planned program includes ambitious demonstration goals, it is recognized that full characterization of the new HTS materials could reveal engineering parameters which impose unforeseen performance limitations. Accordingly, DoD HTS program activities must be governed at any given time by what makes sense at that time rather than by strict adherence to a preconceived plan. Indeed, the possible projects outlined in this document might better be regarded as a map of territory worth exploring in more depth, rather than as a predetermined itinerary. As greater scientific understanding is acquired, and as sound engineering parameters are determined, applications and demonstrations can be undertaken with greater confidence and according to more rigid plans.

Subject to the above limitations, this document sets forth a menu for a five-year Department of Defense Superconductivity Research and Development (DSRD) program. Its goal is to assure that the revolutionary potential of HTS is realized at the earliest opportunity for military applications including both small-scale applications (sensors, Josephson-junction (JJ) electronics, and superconductor-semiconductor hybrid electronics)

and large scale applications (magnets, rotating machinery, energy storage, electromagnetic guns, and directed energy weapons). Included below are (a) mention of the accomplishments and extensive program management experience of DoD in both the science and military applications of superconductivity and of ceramics, (b) an exposition of the rationale for the scope of DSRD, (c) several sections describing research, development, and demonstration projects which would be included in DSRD (including in each case the proposed additional level of effort above and beyond existing relevant program activity and funding), and (d) an overall summary of DSRD budget requirements. Two Supplements (not parts of this report) provide (a) an inventory of ongoing and planned DoD superconductivity activities and (b) some possible options for managing and funding DSRD activity.

It is important to emphasize at the outset that DSRD will seek to integrate the scientific and technical capabilities of academic, industrial, and government laboratories in this endeavor and is pledged to close cooperative coordination with other superconductivity R&D activities, both federal and private. In fact, the program outlined here must be viewed as only a first iteration, one which must be further shaped and adjusted so that it will join gracefully with programs of other federal agencies into an integrated federal program.

DSRD will encompass a spectrum of activity extending from research through exploratory development to demonstration.

Contracts will be awarded for efforts ranging from single investigator activities, through multi-investigator interdisciplinary activities, to multi-organizational collaborations among university, government, and industrial scientists and engineers. The complexities, not only of the HTS materials themselves, but of the associated processing, and of the applications, dictate altogether that single-investigator awards comprise a relatively small fraction of the total level of effort.

It is intended that DSRD provide a shared DoD tech-base reservoir of HTS knowledge and expertise which may be called upon by DoD program managers in support of their separate development projects. However, this proposed program should not be taken too literally, for, as already emphasized, HTS is still in an embryonic stage. Moreover, the intensity and the diversity of worldwide activity are unprecedented, and so it would be unrealistic to claim that an optimum script for DoD activity could be dictated with certainty ahead of time. Accordingly, this program plan should be viewed only as a broad outline of problem areas which must be investigated if the full promise of HTS is to be realized. Those aspects ultimately addressed by DSRD will necessarily be determined in some considerable measure by the pace at which understanding emerges world-wide in areas which relate most directly to DoD applications. Examples of applications for the Services and for NSA appear on the pages at the end of this introduction. These lists are necessarily incomplete and are intended only to be representative of the wide spectrum of

potential applications areas. It is immediately apparent that there are many domains of mutual interest and that all of the above DoD organizations will profit from a well integrated approach. It is also evident that many of the listed military applications, if successfully developed, will have important impact in the civil and commercial sectors as well. Similarly, DoD applications will profit significantly from the very active superconductivity programs being pursued by DoE, NSF, DoC, and NASA. Close coordination with those efforts is already in effect, and awareness of foreign developments is being facilitated by DoD overseas liaison activities in Europe and in the Far East.

POTENTIAL ARMY APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTIVITY

SMALL-SCALE APPLICATIONS

1. Optics and Infrared

    Sensors for focal plane arrays-detection/signal & image processing/JJ detectors/AD conversion/memory devices

    Superconducting/semiconducting optical mirrors

    Novel light modulators (spatial, temporal)

    Specialized electrooptic devices-merged superconductor/semiconductor hybrids/contacts

    Displays-semiconductor/superconductor hybrids for command and control applications

    Homodyne/heterodyne detection systems

    Optical beam steering

    Q-switching for lasers/wavelength shifters

2. Microwave and Millimeter Wave

    Sub-millimeter wave sources

    Millimeter wave integrated circuits

    Millimeter wave/microwave components-amplifiers/mixers/detectors/processors/AD converters

    Low-loss transmission lines

    Superconducting waveguides for Q-switched millimeter wave sources

    Antenna arrays and structures

3. Novel Superconductor/Semiconductor Superlattice and Quantum-Coupled Devices

4. Magnetic Components/Detectors

   Mine neutralization

   Mine detection

   Magnetic components for RPV applications

   RF-protected (EMP) devices

   Magnetic confinement for magnetic circuits

5. Fusing Devices

   SQUID's (Magnetic field detectors-fuses)

   Josephson junction (JJ) electronic devices

   Temperature/pressure switching

6. Specialized Chemical/Biological Agent Detection Materials and Devices (tentative)

7. Inertial/Geomagnetic Guidance Systems

LARGE-SCALE APPLICATIONS

1. Free Electron Lasers

2. Gyrotrons

3. Field Power Supplies, Motors, Generators, Batteries

4. Aircraft (Helicopter) Electrical Power Generation

5. Switches and energy Storage Devices for DEW/High Power Lasers/Nuclear Simulations

6. Electromagnetic Guns/Launchers

POTENTIAL NAVY APPLICATIONS OF HIGH TEMPERATURE SUPERCONDUCTIVITY

SMALL-SCALE APPLICATIONS

1. Infrared
   - Focal plane sensors
   - Multiplexers
   - A/D converters
   - Signal processing
2. Microwave and Millimeter Wave
   - Mixers
   - Amplifiers
   - Phase shifters
   - Transmission lines
3. SQUID Magnetometers
   - Mine detection
   - Submarine detection
   - Surveillance
   - ELF communications
4. Computing
   - Massive Data Processing
   - High-performance, low-power signal processing

LARGE-SCALE APPLICATIONS

1. Ship Propulsion and Power Systems
2. Magnets for Microwave and Millimeter Wave Generators
3. Free Electron Lasers
4. Energy Storage and Pulsed Power

POTENTIAL AIR FORCE APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTIVITY

SMALL-SCALE APPLICATIONS

1. IR - Sensors

   Multiplexers

   Digitizers

   Signal processors

2. mm Waves -

   Receivers

   Antennas

   Wideband processors

   A/D converters

3. Digital Computation

   High performance computing

4. Magnetic Sensing

LARGE-SCALE APPLICATIONS

1. Magnets for:

   TWTs

   FELs

   Motors

   Generators

   Energy storage

POTENTIAL NATIONAL SECURITY AGENCY APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTIVITY

ANALOG

1. Microwave/Millimeter Wave

   Wideband mm wave transmission lines

   Low-noise mm wave detectors, mixers and amplifiers

   Multi-GHz chirp transform processors

   High performance small antenna arrays

   Multi-GHz A/D conversion

2. HF-VHF

   Very large analog signal multiplexing

   HF/VHF high dynamic range mixers

   Ultra-linear A/D conversion

3. Analysis Equipment

   Sampling oscilloscope

   60GHz BW network analyzer

   Transient event recorder

   A/D converter for multi-gigabit recording

4. Sub H-F

   Wideband, high dynamic range ELF receivers

   All digital magnetic sensors

DIGITAL

1. Back-plane zero resistance power bus
2. Back-plane "dispersionless" transmission lines
3. Superconducting/semiconducting cross-bar switch
4. Multi-sensor multiplexers
5. Supercomputing

II. DoD SUPERCONDUCTIVITY ACCOMPLISHMENTS AND EXPERIENCE

Nearly forty years ago, DoD was the first among U.S. Agencies to fund low temperature research on a broad scale, both in-house laboratories and through contract research programs. By providing helium liquefiers for a multitude of universities, and by providing related research funding, DoD pursued a vigorous and productive program in superconductivity. Today most well experienced U.S. superconductivity researchers have either received DoD superconductivity research support, or are second or third generation students of professors who did.

Early DoD superconductivity efforts addressed superconducting bolometers for the detection of infrared radiation, primitive superconducting digital computer switches, and magnetically suspended superconductor gyroscopes. In the basic science arena, F. London's classic works on superfluidity and on the macroscopic theory of superconductivity were published under the aegis of DoD. Shortly thereafter DoD-funded researchers made fundamental contributions on the isotopic dependence of the superconducting transition temperature, and this provided a firm experimental basis for development of the microscopic theory of superconductivity. In the late 1950s DoD-funded research on the microscopic theory of superconductivity led to the celebrated Bardeen-Cooper-Schrieffer theory, for which the authors were awarded the 1972 Nobel Prize in physics. Also, over the years DoD funded researchers who made significant contributions to the

steady advance of the highest temperatures at which superconductivity could be observed.

In the early 1960s DoD-funded researchers made essential contributions to the science of the Josephson junction (JJ) and to the understanding of high-magnetic-field, high-current-density superconductivity. The JJ studies and other superconducting device studies made possible magnetic and electromagnetic sensors of unprecedented sensitivity. The military potential of such sensors has been explored by DoD for magnetic detection of submarines and for the detection of weak electromagnetic signals from extremely low frequencies (ELF) through radio frequencies (RF) to the microwave region. There have been significant related technology-transfers to the civil sector in magnetocardiography, in magnetoencephalography, in magnetic geological prospecting, and in detectors for radio astronomy.

In the area of superconducting electronics DoD programs have made significant progress in both digital and analog superconducting electronic circuits, achieving the highest-quality transmission lines and the highest-speed electronic signal processors. In a joint DoD-IBM program very significant progress was made toward development of a very compact but very-high-speed computer. Subsequent DoD contracts with a small firm, Hypres, Inc., demonstrated ultra-high-speed superconducting electronics based on high-performance more-stable materials. A spin-off of this activity is the world's fastest sampling oscilloscope, now

available commercially as a diagnostic tool for development of high-speed semiconducting circuits, most of which will ultimately find use in military systems.

DoD has also been at the forefront in a number of aspects of large-scale superconductivity technology. The pioneering superconducting cavity resonator particle accelerator at Stanford University was developed under a Navy contract. Moreover, on a small test-bed ship the Navy has demonstrated the feasibility of superconducting generators and motors as replacements for heavy and cumbersome reduction gears as a means for transferring the high-RPM power from a shipboard gas turbine to the low-RPM power needed to drive the ship's propellor. In an Air Force program a very lightweight, ultra-high-power-density superconducting generator was developed and tested as an approach to provision of electrical power for airborne directed energy weapons. In another large-scale military application the very high magnetic fields required for gyrotron millimeter wave generating tubes were provided by superconducting magnets. Such tubes are essential for advanced microwave and millimeter wave surveillance, guidance, and communications systems. Parallel commercial large-scale superconductivity efforts have led to use of superconducting magnets in the now-ubiquitous magnetic resonance medical imaging systems and in prototype electric generators suitable for public power grid applications. All of these civil applications can trace their origins in one way or another to early insightful DoD investments in superconductivity R&D.

Cited above are just a few examples of the very vigorous DoD efforts to provide, by means of superconductors, military capabilities which cannot be achieved by conventional means. The fact that superconductivity has not to date achieved widespread use in operational military systems is attributable primarily to the degree of refrigeration which has been required heretofore. In an effort to mitigate this obstacle, DoD has actively pursued the development of efficient refrigeration systems. In one very elegant example, DoD funded development of a miniature refrigerator, for which the heat exchanger, expansion orifice, and cold region are all contained in a thumbnail-size chip. Although this micro-miniature refrigerator has not yet achieved the very low temperatures required for the earlier generation of superconducting devices it is finding use for cooling semiconductor infrared sensors in missile guidance systems and for cooling the highest speed semiconductor chips. Now that the era of HTS has arrived, this remarkable little refrigerator will find widespread use with superconducting sensors and electronics. Indeed, successful tests with HTS materials have already been carried out.

On a broader scale, the era of HTS offers the potential that the myriad superconducting military applications, pursued so assiduously by DoD over the past forty-odd years will finally come to fruition. With a vast reservoir of knowledge and experience in superconductivity DoD is well poised to exploit the new-found promise of the novel HTS materials.

III. DOD CERAMIC PROCESSING ACCOMPLISHMENTS AND EXPERIENCE

The new high temperature superconductors are ceramics, and thus exhibit many of the same properties as structural and electronic ceramics - brittleness, special processing requirements for both bulk and films, and the need to understand and exploit the defect, crystal, and micro structures to optimize utilization. Fortunately the DoD is in an excellent position to capitalize on its extensive past and present expertise in ceramics science and engineering.

In the late 1960's DARPA Initiated the Ceramic Turbine Program, which turned out to be the major stimulus for the development of today's high technology domestic structural ceramics industry. DARPA has continued its involvement in support of research on synthesis, processing, and fabrication of ceramics and ceramic composites aimed at a variety of DoD applications. Each of the three services has strong efforts and technical expertise in the chemistry, processing and characterization of ceramics, as exhibited by comprehensive contractual and in-house efforts in the Navy (ONR, NRL), Air Force (AFOSR, AFML/AFWAL), and Army (ARO, AMTL).

This extensive materials science expertise coupled with DoD's experience in superconductivity provides a very sound technical basis for DoD to engage in a major R&D effort in high temperature superconductivity.

IV. RATIONALE FOR PROGRAM SCOPE OF DSRD

The primary emphasis of DSRD is on exploitation of the new HTS materials directly, and so every effort will be made to execute applications directly with the new materials. However, it is recognized that in some instances a prolonged period may be required for development of the necessary processing capabilities. In some such instances, those in which there is considerable urgency for demonstrable capability, the shortest path to demonstration will consist of executing the development in proven lower-temperature materials initially and then subsequently executing it in HTS materials. It is pertinent also that some DoD superconductivity R&D activities initiated prior to the discovery of HTS are currently addressing issues both in conventional superconductivity and in HTS. It is essential that some of those efforts using conventional superconductivity be continued as the most rapid and efficient means for testing concepts and architectures which will later be executed in HTS materials. Of course the lowest-noise sensors and lowest-noise electronic components will always have to be operated at the lowest temperatures, and so continued efforts on the most easily fabricated stable materials will continue to be appropriate for such applications.

Included within the scope of DSRD are basic characterizations of known HTS materials, searches for still higher temperature superconductors, approaches to processing both for planar

structures (films), and for bulk materials (wires, cables, rods, bars, monolithic bodies, and tapes), determinations of physical and chemical behavior, advancement and exploitation of small-scale applications (sensors, superconducting electronics, superconducting-semiconducting hybrid electronics), and the technology which relates to large-scale applications (magnets, motors, generators, shielding, electromagnetic guns, and directed energy weapons). In each instance there is a clear rationale for DoD presence.

For all applications both small-scale and large-scale, it is essential for optimum utilization that candidate materials be fully characterized with regard to composition, crystallographic structure, defect state, and microstructure. Also required is knowledge of both normal-state and superconducting-state electrical, magnetic, thermal, and mechanical properties. Such data are essential not only as the basis for engineering development, but are essential as well for theory building in the search for materials capable of still higher performance.

Such a search for new HTS materials is also an essential component of DSRD. In a field so fast moving as HTS, it is most unlikely that the optimum materials for the myriad potential applications have yet been identified. Two analogies provide instructive insight, the progression in semiconductor electronics and the progressions in earlier-generation small-scale and large-scale superconductivity applications. In semiconductor

electronics the earliest material of choice was germanium, which was soon supplanted by silicon. While silicon remains supreme in the majority of applications there are many special applications, especially ultra-high-speed military applications where only compound semiconductors with special superlattice and quantum well structures can provide the required performance. In small-scale superconductivity (electronics) the progression was from soft materials like lead to nobium and then to niobium nitride. In large-scale superconductivity (magnets) the progression was from niobium to molybdenum-rhenium alloys to niobium stannide to niobium-zirconium alloys, and finally to today's workhorse material, niobium-titanium alloys. Add to the above the fact that the compositions and structures of the new HTS materials are highly complex, and it becomes evident that extensive regions of compositional and structural space must now be explored if we are to be assured that we have identified the optimum materials for the many and varied applications. In the meantime, several of the HTS materials already discovered will doubtless find wide use in a variety of near-term applications.

While DoD will surely benefit significantly from efforts of other organizations (DoE, NSF, DoC, NASA) in areas of materials characterization, theory, and search for high-transition-temperature materials, it is essential that DSRD itself include substantive activity in these arenas. Much of the remainder of DSRD activity is so highly applications driven that DSRD characterization, theory, and search activities are essential as a

means to provide focus in directions of greatest perceived impact on DoD applications. Weight considerations are paramount in many DoD applications (as in those of NASA), and DoD has other stressing requirements related to mechanical and thermal shock, as well as to radiation hardness, all of which dictate that DoD-specific characterization investigations be pursued.

In a similar manner, DSRD activities in the area of materials processing will be specially attuned to DoD applications foci. The term "processing" here is used in the full sense of its meaning within the materials science and engineering discipline. The crucial role of ceramic processing in the successful investigation and exploitation of HTS materials cannot be overemphasized. A generic science and engineering base does not yet exist for this field. However, the outlook is encouraging that R&D in ceramic processing will lead to progress overall. This has been the case for defense-related processing activities which have been pursued over the past two decades, especially for applications such as radomes, IRdomes, gas turbine (and other) engines, armor, and transducers. Thus, DSRD processing activities will encompass studies of precursor materials, densification, deposition, crystal growth, etc. Underlying science investigations will address crystal chemistry, compositional phase equilibria, optimum routes to materials synthesis, materials compatability, and protective measures. Most importantly, methods and mechanisms for producing material of the desired composition, structure, defect state, surface state and properties in the

geometry required and in conjunction with non-superconducting materials of the required characteristics are to be emphasized. So as to realize the full benefits of synergism, the DSRD processing activities will be closely coordinated with those of other agencies and of industry, but, as noted above, will be focussed in directions determined by the unique requirements of DoD.

The high accomplishment and extensive experience of DoD in the advancement of superconducting sensor and electronics technology provide a firm base for further DoD exploitation with the new HTS materials. DSRD seeks to further that exploitation. However, because commercial electronics-technology-based industrial organizations (e.g., IBM, AT&T Bell Laboratories) have undertaken aggressive R&D programs in HTS, it might, at first consideration, be argued that DoD should simply wait for those organizations to complete such R&D and only then step in and utilize the commercial organizations' R&D results. This approach is not appropriate, however, for although there are significant areas of overlapping interest, DoD has many specialized sensor and electronics requirements which commercial firms have no incentive to satisfy. For example, one need only compare civil radar to military radar or, alternatively, to consider acoustic anti-submarine warfare signal processors (which have no civil counterparts) to appreciate the unique demands made by military requirements. It is pertinent

that DoD has for many years funded effort at the National Bureau of Standards (DoC) and other laboratories to address specialized DoD needs in superconducting electronics.

DSRD also includes substantial activity related to large scale applications, which arise from DoD requirements for compact high-energy-density electric motors and generators; for magnetic energy storage systems; for pulsed electrical power systems; for magnets; for compact accelerators, free electron lasers, and particle beam systems; for electromagnetic guns; and for gyrotron magnets. Experience has shown that nearly every such magnet-type application requires its own custom designed and fabricated superconducting winding material and winding configuration. Thus there is *need within DSRD for significant involvement with the* science and technology of high-current-density, high-magnetic-field superconducting wires, cables, bars and the like. It is fully recognized, however, that this is an area in which DoE can, by a considerable margin, boast of the greatest experience, the largest past investment, and the greatest accomplishment, albeit often for different systems applications. Accordingly, very close collaboration between DSRD and DoE will be maintained, and every effort will be made to profit from DoE experience.

V. DSRD PROGRAM WORK STATEMENTS

A. Characterization of and Search for High Temperature Superconducting Materials

While there is sound justification for excitement regarding possible applications of HTS it is much too early to perceive the ultimate impact of this remarkable new technology. The challenge is to chart a course which will allow early utilization of first generation HTS materials in near-term applications, while at the same time very vigorously pursuing the search for later generation materials which may offer still higher performance characteristics. A very aggressive program in materials characterization is key to both of these efforts. Such a program will provide the hard data needed. Also to be determined are engineering parameters which are essential for successful design of high performance devices and systems. At the same time, such data will enable comparisons to be made with existing theories and models, and thus will contribute to the development of new theories, concepts, and models which help chart the path toward still-high-performance later-generation materials.

In what follows we catalog (by no means completely) the manifold of characterization measurements which are essential or, at the very least, pertinent to the successful engineering utilization of HTS materials and to the search for still-higher-

performance materials. The complexity of this manifold, and the large number of first generation materials which deserve attention, taken together, represent a matrix of pertinent activity which is prodigious in magnitude and humbling in its complexity. The corresponding characterization matrix for the earlier, or traditional, low temperature class of superconductors was explored at a slower pace over a period of three-quarters of a century, and the corresponding knowledge base which painstakingly emerged has provided a road map for charting the investigations of the new HTS materials.

Clearly, because of the intense worldwide activity in HTS, it will be difficult indeed to execute systematic and optimum courses of exploration no matter how carefully planned in advance. Hence, the most effective program will doubtless be one which (a) is highly flexible, (b) samples at a relatively modest level a broad spectrum of characterization space, and (c) focuses in depth only on selected aspects which are perceived as most pertinent to the applications of concern to the sponsoring organization. DSRD will follow such a course, directing sharp focus on aspects which most directly impact DoD requirements for sensors, electronics, and the variety of high-magnetic-field, high-current-density applications mentioned elsewhere in this proposal.

Listed below are the types of measurements and experimental and theoretical investigations which will be undertaken to achieve

progress in materials optimization, in engineering applications, and in the search for still-higher-temperature materials:

<u>1. Transition temperature, T_c</u>, as a function of chemical composition, of crystallographic structure, of isotopic composition, and of pressure. T_c data define operating temperature ranges and provide clues for the search for higher T_c materials.

<u>2. Energy gap, 2Δ</u>, as a function of temperature, magnetic field, and orientation. Also fluctuations as a function of temperature. These are essential design parameters for a host of sensor and electronics applications based on quasi-particle (or Giaever) tunneling phenomena. If, as expected, the energy gap is highly anisotropic, complexities will be introduced into design, materials processing, and manufacturing. Large anisotropy might also provide opportunities for novel device concepts not possible with more conventional isotropic superconductors. The larger energy gaps of the HTS materials suggest that HTS sensors and electronics will operate at higher voltage levels than are characteristic of earlier lower temperature superconductors.

<u>3. Magnetic field penetration depth, λ</u>, as a function of temperature, magnetic field, and orientation. These data determine at what specimen thickness "thin-film" phenomena begin

to appear. This must be known for successful design of superconducting sensors, electronic circuits, and film-based magnets.

4. Josephson junction (JJ) tunneling and weak-link phenomena as functions of junction structure, temperature, current, voltage, magnetic field, crystallographic orientation, and incident electromagnetic radiation. Also device/structure noise as a function of temperature. All of this is essential information for design of JJ superconducting electronics (memory, logic, signal processors), SQUID magnetic sensors, electromagnetic radiation sensors, voltage standards, and voltage-tuned local oscillators.

5. Interaction of HTS materials with electromagnetic fields. The zero resistance property of the superconducting state is only correct at "zero" frequency. At finite frequencies there are small, but detectable, electrical losses (especially at large oscillating voltages) which influence the performance of superconducting devices operating at finite frequencies from 60 Hz (for machinery or power applications) up to frequencies corresponding to the superconducting energy gap of the material. (At frequencies greater than the gap, the material exhibits normal-state properties.) These measurements must be made as functions of material configuration (thin film, wire, conductor, etc.), processing parameters, microstructure, annealing, etc.

6. Interactions of HTS materials and devices with optical radiation. These investigations will explore the feasibility of photonic devices analagous to those already highly developed for semiconductor-dielectric structures. This will be carried yet a step further to explore concepts for electronic-photonic devices which make use of semiconductor-dielectric-superconductor structures.

7. Thermodynamic properties, viz., specific heat and magnetization, both as functions of temperature and magnetic field. Such investigations provide measures of superconducting state condensation energy, which, in turn, is a measure of the extent to which inhomogeneities might be introduced to stabilize dissipationless high-electric-current densities at high magnetic fields. Condensation energy is thus an important index of merit for a material relative to its suitability for supermagnet applications.

8. Critical magnetic fields (viz.: lower critical field, H_{c1}, or magnetic-flux-penetration-onset field; upper critical field, H_{c2}, or upper-field limit of the Abrikosov vortex lattice phase; and sheath critical field, H_{c3}, or upper-field limit of surface superconductivity) all as functions of temperature and of orientation. These fields define the available magnetic-field and temperature operating regimes for superconducting materials in a variety of applications. For example, supermagnets typically

operate at fields of the order of one-half to two-thirds of H_{c2}, while superconducting cavity resonators must operate in the Meissner phase such that supercurrent vortices are absent.

9. Approaches to controlled introduction of material inhomogeneities suitable for pinning supercurrent vortices as a means for stabilizing high-electric-current densities at high magnetic fields. This is the key to the attainment of superior supermagnet performance. Features such as precipitates, ordered defects, and voids will be considered.

10. Determination of the magnetic-field/current-density/temperature critical surface for promising supermagnet materials. In practice the operating point for a material in a supermagnet must lie inside this surface.

11. Mitigation of magnetic flux flow, creep, and jumps. These effects, which occur under various transient and quasi-steady-state conditions, are loss factors in supermagnets and must be taken into account in magnet design. This area requires special attention, because the level of thermal activation contributing to flux creep and flux jumping is of the order of twenty times greater at liquid nitrogen temperature than at liquid helium temperature. Accordingly, if the new HTS materials are to support large current densities at high magnetic fields at liquid nitrogen

temperatures their superconducting condensation energies must be large enough to allow insertion of very deep potential wells to serve as vortex trapping sites.

12. Mechanical and thermomechanical aspects. In electromagnets the interactions of winding currents with generated magnetic fields give rise to large mechanical stresses. Hence, for engineering design purposes, data are required on tensile, shear, and compressive moduli (by quasi-static and by acoustic techniques), and on failure stresses. Because supermagnets are cycled periodically in field, leading to periodic applications of stresses, fatigue factors are of importance, particularly for brittle ceramic materials. For materials with exceptionally high operating temperatures stress corrosion effects may very well become important. Both in magnet applications, and in sensor and electronic applications, superconducting materials may be used either in contact with or in composite form with other materials. Hence to achieve adequate thermomechanical compatability in engineering designs, appropriate thermal expansion data must be obtained for all components, superconducting, normal, and insulating. However, because perfect thermal expansion compatability can never be achieved, consideration must be given to fatigue effects which stem from thermal cycling. These considerations apply of course to both large-scale (magnet) and small-scale (sensors and electronics) applications.

13. Thermal and magnetocaloric effects. All sources of thermal input to both small-scale and large-scale superconducting systems (in addition to those already discussed above) must be determined. In addition, data are required on thermal conductivity and thermal diffusivity. Taken altogether such data will permit thermal design engineering which provides for adequate heat removal. As an ancillary aspect of this activity, magnetocaloric effects in the new HTS materials deserve consideration on the possibility that they could provide a basis for a magnetization refrigerator, in which the HTS material serves as the working substance. Prepared in highly homogeneous form high-magnetic-field superconductors cool upon being magnetized.

14. Electromigration effects. In conventional microelectronic circuits the combination of high current density and elevated temperature can lead to destructive migration of materials. The possible onset conditions for such effects both in small-scale and large-scale superconducting applications will be investigated.

15. Atomic level structure. Full characterization of HTS materials at the atomic level is essential for optimization of existing materials and for progress toward development of superior new materials. The full powers of the following very effective bulk and surface approaches are required: x-ray crystallography, neutron scattering crystal structure determinations, transmission electron microscopy, scanning electron microscopy, nuclear

magnetic resonance, electron spin resonance, Auger spectroscopy, low energy electron diffraction, and scanning tunneling spectroscopy.

16. Chemistry. In-depth crystal chemistry plays the central role in materials synthesis and in the understanding of the complex compositional-phase diagrams in which useful new materials are to be found. Chemical factors are also of importance in the correlation of structure with properties and are key to design issues concerned with chemical interactions, protective coatings, stability, and compatability of HTS materials both with other materials and with liquid, vapor, and gas ambients. Oxygen and other atomic diffusion information is critically needed to determine the time/temperature requirements for fixing stoichiometry during annealing, as well as to predict the long term chemical compositional stability. Research on single crystals or single-phase polycrystals is preferred, but some studies on multiphase polycrystals may be warranted. Phase diagram and chemical reaction kinetics determinations and compilations are vital. This should include oxide as well as rare earth metal phase equilibria studies. It is important to establish chemical reaction kinetics between the ceramic superconductors and materials with which they will be in contact during processing and subsequent use.

17. Effects of ionizing radiation. In a number of applications HTS materials will have to operate in ionizing radiation

environments. It is thus essential in engineering designs to explore, understand, and take account of the whole range of radiation effects, from transient upsets in superconducting electronic circuits with no resulting permanent damage, all the way to high flux radiation effects capable of producing massive and permanent damage. There is also the possibility of employing radiation processing as a means for enhancing desired properties in some instances.

18. Experimental comparison with Ginzburg-Landau-Abrikosov-Gorkov (GLAG) macroscopic theory. Evidence to date suggests that the new HTS materials are GLAG type II superconductors. However, design and development activities on HTS devices and systems cannot be undertaken with confidence until full comparisons of experiment with GLAG theory have been carried out. This will involve measurements of H_{c1}, H_{c2}, and H_{c3}; observation of the supercurrent vortex lattice of the mixed state; determinations of the Ginzburg-Landau kappa value from transition temperature and normal state parameters (electronic specific heat and normal-state electrical resistivity, ρ_n); and determinations of thin film superconducting properties. Some necessary modifications of the theory can be anticipated, viz., provision for effects of a strongly temperature dependent ρ_n (which will markedly alter penetration depth, coherence length, and kappa, and hence the whole manifold of critical fields and film properties), and most probably the need for inclusion of electronic anisotropy because of the layer-like

or linear character of HTS materials. This latter characteristic could have profound impact on the ultimate utility of the new materials.

19. Experimental comparison with microscopic theories. Tests of the degree of compatability of the Bardeen-Cooper-Schrieffer (BCS) microscopic theory with the new HTS materials are of critical importance. The apparent absence of an isotope shift in the observed transition temperature of some HTS materials suggests that the electron pairing interaction in these cases may not be phonon mediated. Phonon energy spectra, as determined from neutron scattering and from quasi-particle tunneling, may help to resolve this issue. Other particularly critical hallmarks of the BCS theory which invite experimental tests are its predictions for acoustic absorption and for nuclear magnetic resonance relaxation times. Such investigations of the intrinsic nature of the new HTS materials will contribute importantly to extensions of the BCS formalism, to creation of new theoretical concepts, and to the search for still-higher-temperature materials.

20. Electronic-energy-band structure and other normal-state considerations. Electronic-energy-band theoretical calculations and corresponding experimental determinations are required as means both to provide understanding of the remarkable electronic structures which give rise to HTS and to suggest promising directions for further HTS search. Of particular value on the experimental side, as means to determine the electronic structure,

are measurements of photoelectron spectroscopy and, if possible, of cyclotron resonance and of magneto-oscillatory phenomena such as the de Haas-van Alphen effect. The latter two types of experiments require low temperatures so that Landau level spacings will be larger than thermal energy, but it appears that at such low temperatures magnetic fields of the order of 100 Tesla might be required to drive the materials into the normal state such that cyclotron resonance and the de Haas-van Alphen effect can in fact be revealed. Also of interest for characterizing the HTS materials are measurements of the magnetoresistance, the Hall effect, and the thermoelectric effects. Not to be overlooked among pertinent normal-state properties, which may relate significantly to the very special behavior of HTS materials, are the normal-state magnetic properties, which, because of the presence of rare earth ions, may include a variety of types of magnetic ordering. If not recognized and not understood, interactions between such magnetically-ordered states and superconductivity could lead to failed designs. Conversely, if such effects are fully understood they may offer useful new design alternatives.

Proposed Budget

CHARACTERIZATION OF AND SEARCH FOR HTS MATERIALS

$M

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	10	13	9	8	6	46
6.2	0	3	6	8	8	25
6.3A	0	0	0	0	0	0
Total	10	16	15	16	14	71

B. Processing

1. Introduction. The present stage of HTS technology is derivative from the revolutionary report from Zurich in 1986 and the subsequent major advances in Houston and elsewhere. This technology generally attempts to exploit the "1-2-3" compounds, i.e., materials based on the copper oxide-barium oxide-yttrium (or rare earth) oxide system. For purposes of this program it has been assumed that these oxide materials, often as polycrystalline ceramics, will be the ones focussed upon for possible use in near-term and mid-term applications. Thus, it is these materials which we must learn how to synthesize, process and fabricate. (It is recognized that HTS is still in a very early stage of development. Thus, it is by no means clear that future R&D will not involve other materials classes such as nonoxidic ceramics, intermetallics, or even polymers. We may have to learn how to process these as well.) The new HTS materials are typically brittle, and this inductile behavior often places special constraints upon the modes of processing available for their fabrication into useful components and devices. The present discussion is intended to represent the flexible beginnings for what must be an ongoing recognition of processing R&D needs and of appropriate solutions for meeting these needs.

The strongest paradigm addressed in the materials science and engineering domain is definition of structure-property

relationships for each particular materials system under consideration. This paradigm says that the structure of a material, at any relevant size scale, whether surface, bulk or atomic in nature, and appropriate to its end-use defines the properties of that material. A less-well recognized paradigm is that such structural features arise from the effects of processing operations used with a particular material. In general, processing refers to the combination of understanding and art which is used to develop and reliably prepare (manufacture) a material's product displaying a desired character (structure, composition and defect state). Ceramic processing must recognize the sensitivity of this character to processing at every relevant size scale, and also control the effects of operations meant to remove material, alter surfaces, or produce bodies or specimens of "large" or "small" size.

These processing operations profoundly influence manufacturing technology of ceramic materials, with derivative cost and reliability concerns. Manufacturing technology is very strongly dependent on techniques, processes, and operations developed during R&D on how materials of interest are densified, shaped, joined, and finished. Depending on the application envisioned, one must be concerned with deposition of thin films (useful for electronic and electrooptic devices) or making of more monolithic configurations (useful for magnet and other power handling applications). Also of concern are methods for preparing single crystal materials, both in bulk and in film forms. The processing

methods are somewhat different for these cases and are considered separately below.

2. Thin Film Materials, Devices and Circuits

a. Introduction. The requirements for processing thin film superconducting devices and circuits are similar to those used in the semiconductor industry. Of high priority are the ability to deposit thin (and thick) films of metallic and insulating materials of defined character and controlled properties, and the ability to process multilayered structures of alternating metal and insulator to be used to detect electromagnetic radiation or to amplify or process the signals obtained from these sensors in either analog or digital format. A successful circuit fabrication technology for electronic circuits must yield chips whose characteristics are controllable and reproducible and which are durable, stable, corrosion resistant, and can withstand extended periods of storage at or near room temperature. Based on experience gained in the semiconductor industry and, to a lesser extent, from earlier, lower-operating-temperature superconducting technologies, a systematic and logical approach for developing a viable high-temperature superconducting electronic integrated circuit technology can be conceived in general principle. However its successful development will demand a very long-term effort of considerable magnitude.

Electronic integrated circuit technology often requires multilayered structures consisting of as many as a dozen alternating depositions of conducting and insulating layers and several dozen processing steps. As each layer is deposited, it is then processed into a desired geometry and then overcoated with the next layer. Thus, to establish a technology base for HTS electronic integrated circuits, one must consider not only the deposition of the superconducting film, but also the deposition of compatible insulating layers and techniques for the processing of these films, both superconducting and insulating, into required geometries. The greatest challenge, however, is the preparation of multilayered structures in a controlled manner so that the deposition and processing of a given layer does not degrade the properties of the previously deposited layers.

In addition, superconducting films will have applications in areas that do not necessarily require the preparation of junctions. For example, a superconducting film can be used to coat a high-frequency resonant structure thereby reducing its resistive losses and enhancing its Q. Superconducting films can also act as shields both to reduce the effects of ambient fields on sensitive electronics as well as to shield surrounding regions from fields originating inside shielded regions. Films may be used to form the high-current, high-critical-field conductors for magnets, machinery, energy storage, and power transmission. In fact, there may be some new approaches to the designs of these systems that take into account the special inherent character of

these materials. The requirements for these devices are in some ways significantly different from the requirements for superconductive electronics, in that they have to be prepared on other than the usual single crystal substrates and must be deposited over large areas and long lengths. Traditional vacuum thin-film deposition techniques, however, have been used in the past to produce similar structures using the more conventional lower-transition-temperature materials.

b. Thin-Film Deposition. Because the recently discovered high-temperature superconducting materials are four-component systems, their deposition as thin films is a challenge. Accordingly, a variety of techniques should be explored and evaluated for the processing of HTS films including the following:

Sputtering (DC, RF, magnetron, etc.)
Thermal evaporation
Electron-beam evaporation
Laser evaporation
Chemical vapor deposition
Liquid phase epitaxy
Vapor phase epitaxy
Laser, ultraviolet, and other techniques for assisting/ enhancing film growth
Rapid thermal anneal (RTA) techniques to optimize film properties
Organometallic film precursor

These techniques should be tried using single crystal substrates to grow the desired film epitaxially in the appropriate crystal structure. Degradation of film properties arising from possible chemical diffusion and interaction between the substrate and the film during deposition or during post annealing treatment must be monitored, and the use of different substrate materials or, possibly, diffusion barriers may have to be considered. In addition, certain techniques associated with ceramic materials, such as the sol-gel and powder techniques should be explored during the initial phases of this program. At the completion of the first year or two, it should become apparent which few techniques for depositing these high-temperature materials offer the greatest potential.

c. Materials Characterization of Films. As thin films of these materials are deposited, they must be extensively characterized, physically, chemically, electrically and magnetically. Specifically, the following characteristics or properties of the thin-film materials which should be determined include:

Composition

Defect state

Crystal structure

Microstructure

Single-phase versus multi-phase nature

Chemical stability and room temperature storage behavior

Surface character and morphology

Mechanical properties including thermal shock response

Adhesion to substrates

Electrical and magnetic properties which should be measured include:

Critical temperature (T_c)

Critical current density (J_c)

Critical magnetic fields (H_{c1}, H_{c2}, H_{c3})

Temperature dependences of J_c and critical fields

Microwave and millimeter wave electrical behavior

Superconducting penetration and coherence lengths

Superconducting energy gap and phonon spectrum

Normal state conductivity

These chemical, physical, electrical, and magnetic properties must be studied and correlated with the fabrication processing used for the preparation of the films. Attempts should be made to optimize the relevant properties as functions of film preparation techniques.

d. Device and Structure Processing. Once clear focus has been given to film deposition techniques, efforts should be accelerated to process these films into thin-film stripes, loops, and Josephson devices. The techniques to produce structures from HTS materials include:

Wet chemical etching

Reactive ion etching

Ion milling or sputter etching

Proton (or other nuclear particle) bombardment

Use of (modified) lift-off lithography

These techniques must be characterized with respect to their controllability and the resultant materials reproducibility, reliability and uniformity, as well as feature size definition, possible damage to untreated regions of film, and compatibility with other (insulating) layers required for integrated circuit fabrication.

In addition it will be necessary to explore various insulating layers (for example, oxides, nitrides, etc.) for isolating metallization layers from one another. The properties of these insulating layers should include:

Pinhole free to insure positive isolation

Prepared by technique that is compatible with those used for preparing superconducting films

Thermal expansion comparable to superconducting films

Good adhesion to HTS films

Good integrity of films over the edge of the underlying HTS film

Sufficiently different etching rates than that for HTS films to facilitate selective processing of multi-layered structures

The selection of candidate insulating layer materials will depend very signficantly on the chemical and physical properties of the high T_c films, which will be determined during the early portions of this program.

Due to the nature of these HTS materials, there may be some difficulty in forming dependable electrical contacts with the required small resistance. Small contact resistance can be achieved by various techniques such as ion milling or sputter-etching the surface of the HTS film prior to depositing a normal metal contact layer or, possibly, by diffusing or implanting some metal to provide the low resistance contact. The technique that will be selected will depend strongly on the nature of the surface of the as-prepared films, which must be determined during the early stages of the program.

Two types of Josephson structures should be explored. The weak link is a narrow constriction in a thin film sample. The primary advantage of this type of Josephson device is that it requires only a single thin film deposition. The primary disadvantages of the weak link are that it exhibits only some of the properties of an ideal Josephson junction and that very stringent requirements are placed on the dimensions of the

constriction. Typically, the width and length of the constriction must be of the order or less than one micrometer. It is relatively easy to fabricate individual weak link devices with the desired dimensions. However, if a circuit containing a number of weak link devices is required, the need to achieve reproducibility of device electrical characteristics, for example, the critical current, places very demanding requirements on the lithography and device processing. The <u>tunnel junction</u>, which can exhibit all of the Josephson phenomena, is more difficult to fabricate than the weak link structure. The tunnel junction consists of two superconducting regions separated by a very thin barrier, which can be either an insulator, a semiconductor, or a normal metal, which is of the order of 1 to 10 nanometers thick. The tunneling of a current across a superconductor-insulator interface is crucially dependent on the coherence length of the superconductor. A very short coherence length in the electrode materials implies the need for high quality superconductor from deep inside the electrode to a distance of the order of a coherence length below the surface. In the case of the high T_C materials, the coherence length has been estimated to be of the order of 1.5 nanometers, which is comparable to the lattice constant of the material. Thus, it would appear that there is a crucial challenge to grow high quality electrode material with bulk properties up to about one lattice spacing below the surface. The second crucial problem to be solved in order to make high quality tunnel junctions with high T_C electrodes is the requirement for high substrate temperatures or high temperature post-deposition heat treatments

to obtain the high transition temperatures. It is straightforward to use elevated processing temperatures for the bottom electrode while elevated processing temperatures for the top or counterelectrode may degrade the properties of the very thin barrier region onto which the top electrode is deposited. Only experimentation with the fabrication of the all-high-T_c tunnel junction will clarify how serious an obstacle the coherence length and the elevated processing temperatures might be for the fabrication of high quality tunnel junctions with both electrodes of high T_c materials.

Once Josephson tunnel junctions and weak link devices have been fabricated, the following characteristics should be studied:

- The transition temperature of the electrodes and of the completed device
- The superconducting energy gap of the device and its temperature dependence
- The sub-gap leakage current and its dependence on processing procedures
- The critical current of the device and its temperature dependence
- Specific capacitance of the junction
- The magnetic field dependence of the critical current
- The chemical, physical, and thermal stability of the Josephson device

Document the variation of critical current density as a function of processing procedure

Determine the limits of currently available device processing techniques for preparing devices with minimum cross-sectional areas and thus exhibiting minimal values of critical current and capacitance

In addition to Josephson devices, electronic circuits require a variety of signal interconnects, inductors, capacitors, filters, signal couplers, etc., which are fabricated by separating superconducting ground planes from narrow thin film "wires" or stripes with a thick insulating layer. The thicknesses of the insulating and the superconducting layers determine the electrical characteristics of the electronic components. Specifically, the development of these components should include the following tasks:

Develop superconductor-thick insulator-superconductor structures

Explore various insulator materials to minimize the electrical loss associated with the insulator

Determine the chemical, physical and thermal stability of these structures

Establish that the lowest electrical loss insulator can provide continuous step edge coverage

After selection of the most promising thin film deposition technique, a multi-layered superconducting integrated circuit technology will be developed. Specifically, the following will be undertaken:

- Select the most promising deposition technique for the fabrication of HTS thin films and HTS Josephson devices
- Establish and document the reproducibility and controllability of fabricating HTS Josephson devices
- Demonstrate the ability to fabricate very fine wires and interconnects capable of carrying current densities greater than $10^4 A/cm^2$ approaching $10^5 A/cm^2$
- Fabricate multi-layered structures containing Josephson devices, interconnects, and passive circuit components; evaluate their electrical, chemical, and phyical characteristics
- If necessary, modify the processing technology to optimize the electrical, chemical and physical characteristics of the HTS thin film integrated circuit technology

In parallel with the development of the above processing technologies, trade-off studies will be conducted on a continuing basis comparing superconducting sensors, electronic circuits, and systems against conventional semiconductor technologies. This

activity will guide demonstration projects in directions determined to offer highest possible payoffs in military capability.

3. Bulk Superconductors. In most bulk superconductor applications the goal is to achieve material structures which will support high electric critical current densities in the presence of high magnetic fields at reasonable operating temperatures. This requires the introduction, on an optimum spatial scale, of inhomogeneities of lower superconducting condensation energy, which will act as supercurrent vortex pinning sites. This stabilizes the vortex lattice against the Lorentz force, resulting (under steady state conditions) in the flow of electric current without dissipation. Heavy emphasis will be placed on development of processing approaches which will result in inhomogeneities of appropraite composition and spatial scale for attainment of the desired operating ranges of current, magnetic field, and temperature. Moreover the brittle HTS ceramics must be made sufficiently robust to withstand the use environment. Several advanced ceramics processing concepts will facilitate manufacturing of bulk superconductors. Vapor deposition of the superconductors (or other methods of processing) onto strong, stiff graphite or metallic fibers or fine wires might provide robust superconducting windings for magnet, motor, and generator applications. Toughening of superconducting ceramic tapes may be achieved by compositing, where debonding of the fiber/matrix interface and fiber bridging will resist catastrophic failure. A

variety of other standard and newer processing techniques (e.g., sol-gel, dynamic compaction) could be employed in one way or another, depending on the desired component microstructure shape and ultimate application.

Any such processing must result in superconductors which have the requisite supercurrent vortex pinning inhomogeneities, chemical composition, and stability (corrosion resistance) sufficient to provide the electrical characteristics required for long-term use of devices and machines. Examples of such requirements are given in the table below.

Application	Critical Current Density	Characteristic Fields
High field magnets	10^4 A/cm^2	20 T
Electromagnetic launchers	10^5 A/cm_2	10 T
Motors, generators, energy storage, mm-wave tube magnets	10^5 A/cm^2	6 T
Magnetic resonance imaging	10^5 A/cm^2	1 T
Power transmission	10^5 A/cm^2	0.1 T

Basic knowledge is required to optimize the processing of these superconductors: oxygen diffusivity in the ceramics; detailed phase diagrams; effect of composition and inhomogeneities on electrical characteristics and corrosion behavior. This information will facilitate selection of the ultimate processing approaches for a particular application. Characterization required is similar to that under V B 2c.

In some ways, the processing of bulk HTS materials is a greater challenge than for thin films. Thus, there must be continuing strong 6.1 and 6.2 programs to explore new processing techniques. While some 6.3A effort is explicitly necessary, most such effort would be part of applications programs such as those proposed in the following sections.

For bulk configurations of HTS materials in large scale applications, it must also be kept in mind that selected programs must be pursued which are generic in nature but which are of direct use to concerns of scale-up and configuration achievement. Nearly every stage of ceramic processing, especially via the solids processing route affects *the evolution* of the character of a material. Special attention will have to be paid to preconsolidation-particulate preparation, agglomerate uniformity, consolidation, elimination of density gradients, final densification mechanisms, impurities, phase equilibria, and texturing.

For the solids processing route, the relationship between preconsolidation, consolidation, and densification and their dependence on starting material character will have to be pursued. Fabrication of bulk parts such as tapes, wires, cables, etc. may be achieved through utilization of recently developed approaches which begin with shaped metallic alloys of appropriate

composition, which are subsequently reacted to yield ceramics of desired composition and shape. This work is in early stages of development.

For the fluids processing route, glass-forming and glass crystallization, chemical vapor deposition, and molten particle spraying may be of great interest for HTS. It is of importance to note that fluids processing is generallly free from direct influence of the behavior of feed particle materials. While these methods are of importance in film fabrication they are suitable for fabrication of dense masses as well. This family of processes might then allow for coatings, surface finishing, and joining for HTS materials. Investigations of these methods are of importance for preparation of very fine-grained materials, porosity-free materials prepared by spraying methods (but in bulk form), chemical vapor deposition for bulk form, and advancement of shaped crystal techniques (growing them directly).

4. Single Crystals. Single crystal growth methods, including cruicible methods, withdrawal methods, flame and other (laser) fusion techniques, zone melting, hydrothermal crystallization, the sol-gel process, electrolyte processes, etc., all might be of use. They should be explored for their potential to yield bulk single crystals. Similarly, the entire battery of thin film deposition methods described in 2, above must be evaluated for their suitability for single crystal film growth. Also of interest might be sol-gel precursors for films.

Proposed Budget

PROCESSING R&D

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
			$M			
6.1	6	9	6	5	4	30
6.2	7	15	17	15	13	67
6.3A	0	2	4	12	14	32
Total	13	26	27	32	31	129

C. Small Scale Applications and Demonstrations

Superconductors exhibit unique properties which allow development of high performance sensors and electronics systems. These unique properties are the following:

Zero DC electrical resistance and very low high-frequency resistance (into the 100GHz range for present low temperature materials).

Exclusion of magnetic flux from the bulk of the material (up to a materials dependent limit).

Quantum effects

- very non-linear tunneling
- zero resistance tunneling
- flux quantization
- AC Josephson effects.

From this list of phenomena, one can readily create an applications list of generic electronics areas where superconductivity can make a difference - from the range of "useful" to "unique and critical." Furthermore, superconductivity at temperatures above approximately 40K creates a host of feasible electronics applications. Refrigerators exist which are compact, power efficient, and light weight in comparison with the normal experience with 4K cooling. In addition, there are cryogenic

fluids whose latent heat of vaporization is 50 times greater than that of helium. This permits either a small volume for the same electronic power dissipation or a 50 times longer operating lifetime for a system compared with its helium cooled counterpart. In addition to these cooling system advantages there is the opportunity to operate semiconductors and superconductors in the same cryogenic environment.

Future semiconductor integrated circuits will be limited severely by propagation delays in interconnects. High-critical-temperature superconductors may provide the means to enhance significantly the speed of future integrated circuits that incorporate ultrasmall (50 to 1000 Angstrom) electric components with picosecond-scale (10^{-12} second) switching times. Likewise, the use of high-critical-temperature superconductors as gate materials portends great speed increases in high-electron-mobility transistors and related ultrafast transistors. Among the many potential application of HTS which depend upon zero resistance, and in some instances upon magnetic field exclusion, are the following:

DC power distribution in semiconductor systems
Very low attenuation transmission lines
Very low attenuation and dispersion digital interconnects
Passive microwave and millimeter wave components
High performance analog filters

EMI shields

EMP shields

Among the many potential applications of HTS which depend upon the unique quantum effects are the following:

Magnetic sensors

mm wave amplifiers, mixers, detectors

IR/UV sensors

Digital logic switches

Digital memories

Ultra linear A/D converters

Such components and circuits can make signficant contributions in the following operational areas:

Devices Circuits	Operational Applications
Magnetic sensors	ASW, ELF
	buried mine location
	land vehicle surveillance
mm wave components	space communications
	space radar
	LPI systems
	ESM/ECCM
	antenna arrays
	laser "chirp" radar

IR sensors	IR seekers focal plane array imaging
A/D converters	communications surveillance ECCM/ESM
Logic/memory	SAR non-acoustic arrays "shared antenna" systems cryptology

There are a number of generic materials-based questions which must be addressed and answered enroute to applying superconductivity to electronic systems. The generic form best suited to present electronic uses is that of films, ranging from hundreds of nanometers to tens of microns in thickness. The format can be full sheets or patterned lines; the method of formation can be evaporation, chemical deposition, even mechanical. To realize advances in the technology of ultrafast electronic devices and circuits, research and development must be undertaken in several areas including: the fabrication and characterization of high-quality superconductor-semiconductor interfaces; the measurement of propagation phenomena, ultrasmall superconducting interconnects/structures and the fabrication of large networks of ultrasmall superconducting interconnects.

For determination of the usable temperature domain for the applications being considered, the critical current density must be determined as a function of temperature for the films of interest. For many uses, the behavior of the films as a function of electrical frequency is critical, because high performance most often translates to mean high speed. It is imperative that the films allow some realistic form of electrical connection: there is a requirement for interface metallurgy which is compatible with both the superconductor and a non-superconducting element. Then there will always be the critical issues of stability, reliability, manufacturability. These materials and processing questions must be addressed in the context of the electronics systems in which they are to be used.

With regard to devices, one expects an improvement in speed for Josephson junction devices made with HTS materials: their higher energy gap results in higher drive voltages for superconducting logic devices and memory cells, while keeping their impressively low power dissipation. One clearly must discover how to make junctions of a quality already well established in the more traditional Nb and NbN superconductive technologies. Of particular importance in this connection is the ability to fabricate high-quality, reproducible insulators suitable for tunneling structures. Arrays of such junctions may be used in very high performance IR sensor applications for use at temperatures even higher than present semiconductor devices.

The use of the new HTS materials for junctions and electronics in magnetic sensing SQUID (superconducting quantum interference device) systems opens up a large number of cost-effective military surveillance and detection possibilities. The cooling efficiency now available and the very low electrical power required for the electronics combine to form remarkably effective and affordable packages which can be carried by individuals or by all sorts of military vehicles (space, air, land, sea), and can be dispersed in intercommunicating arrays so as to realize the benefits of array processing.

In what follows, approaches to a number of specific small-scale applications are outlined. Although uncertainties preclude definitive prioritization of these applications, an attempt has nonetheless been made to order them such that those listed earliest appear to offer prospects for earliest realization.

1. Magnetometers and Gradiometers. The most useful technology for measuring magnetic fields weaker than 10^{-8} Gauss relies upon superconducting SQUID's. Systems have been fielded at 10^{-9} to 10^{-11} Gauss and have been used in both test and operational situations. The unique feature is the very large dynamic range with a frequency response from DC to tens of kilohertz. The principal drawback today which has limited wider acceptance of this technology has been the inconvenience of the cryogenic cooling system. Essentially all such present systems are liquid helium cooled. If the new HTS materials can produce SQUID sensors

of substantially the same sensitivity that present ones offer, then a number of very important applications may prove to be practical.

Gradiometers and magnetometers for submarine detection could be fielded with small 1-year hold-time dewars or very low electrical power refrigerators thus greatly enhancing the reliability and support logistics. Such systems could reduce the detection time and uncertainty of airborne submarine detection systems. Such high sensitivity sensors, if ground based, could be used for the detection and surveillance of large vehicles (e.g., trucks, tanks) as well as for mine detection and localization. Arrays of such devices could readily be deployed, interconnected, and queried so as to realize the well known advantages of array processing.

The overall advantages of HTS SQUID magnetometers and gradiometers are unmatched sensitivity (either long distance to or small signal strength of target), reasonable sensor size, exceptionally low power, and long (if necessary) mission time.

It will be the goal of this activity to develop and evaluate HTS SQUIDs for use in magnetic field sensing instruments capable of flux sensitivity $10^{-10} G/\sqrt{Hz}$.

Sensors - The choice of "weak links" versus Josephson junctions as magnetic field sensing elements is highly materials

dependent, e.g., are tunnel junctions manufacturable and reliable using these new materials? Experimental investigations will be made to determine if one type is superior in this application or if both are viable, and one or both will be characterized.

Circuits - Both DC and RF SQUIDs have been successfully implemented using conventional superconductors with the choice depending on the requirements of the applications. Once the characteristics of the new HTS sensors are known, DC and RF SQUIDs will be simulated, and their performance will be experimentally verified.

Noise Measurements - After the feasibility of DC and/or RF SQUIDs has been established, they will be thoroughly characterized with respect to noise at all frequencies of interest and while operating at temperatures above 27K.

Digital SQUIDs - The basic SQUID sensing element will be integrated with superconducting or semiconducting digital circuitry operating at the same temperature to form an all digital system. Such a system will be designed, simulated, fabricated, and tested.

Proposed Budget

MAGNETOMETERS AND GRADIOMETERS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	2	1	1	0	0	4
6.2	2	2	1	0	0	5
6.3A	0	3	1	0	0	4
Total	4	6	3	0	0	13

2. Hybrid Semiconductor-Superconductor Systems. Superconductive devices do not, at present, offer the circuit designer the flexibility to which he is accustomed. For example, power gain logic gates and good "three-terminal" behavior are not yet available. There are systems where semiconductors can perform very well but wherein superior performance can be achieved by the proper use of superconductivity, both in passive components and active devices. The resulting hybrid system can even perform tasks which, at present, neither technology can accomplish alone.

A most attractive and relatively "easy" use of high temperature superconductivity is in the backplane wiring used in multi-chip semiconductor systems. In order to achieve high reliability and high performance, systems designers are beginning to use cryogenically cooled semiconductors. As the speed increases, the speed demands on the interconnecting transmission lines become significant and a problem. Increasing the transmission line width means that one also increases the number of wiring levels - a costly change. If the properties of the new HTS materials approach those of present low temperature superconductors, long path length ($\sim$100cm), high speed, ($\ll$1ns rise time) pulses can be carried on very narrow lines, possibly on two planes. In addition, because the critical current densities of the new materials appear to be greater than $5 \times 10^5 A/cm^2$ (at present) one can readily consider power distribution with zero resistance lines of 10μm width. This could permit greatly reduced

switching noise and two dimensional power distribution of very large (~1000W) supply currents to a large multichip system.

Focal plane array systems using semiconductor detectors can be greatly improved if the preliminary multiplexing and digitizing are accomplished with superconductive devices. The high speed and low power consumption can provide an easy interface to both the sensor and warmer temperature electronics. The cooling requirements for these electronics functions can be reduced by at least a factor of ten compared with present solutions.

Millimeter wave receivers, wherein cooled HEMT devices produce the amplification, and superconductive interconnects carry the signals, can result in greatly enhaced bandwidth and improved noise performance. The use of a superconductive mixer may also be considered for an added improvement. In some configurations, particularly at sub-millimeter wave lengths, semiconductor amplifiers are, as yet, not effective. Then, a superconductive paramp or a superconductive mixer may be required; one can then filter the IF and amplify with a low-noise cryogenically-cooled HEMT device. Such hybrids exploit the best of two technologies.

The directions being taken by supercomputing architects for future systems envision the use of tens to thousands of separate processors connected to commonly accessed memories. Such massively parallel systems demand very fast ([illegible] 100ns) memory access with conflict resolution. The [illegible] relatively

less expensive, slower processors may be used in order to achieve hundreds of times the performance of a single or small number of 10ns clock rate processors. By exploiting the unique zero resistance of superconductivity and Josephson devices, one may be able to build a very fast ($\sim$1ns latency) switch network to interface between these room-temperature technologies. The applications of such large parallel systems are very important and widespread: SONAR, RADAR, weapons, and hydrodynamic calculations, to name a few.

As a subset application of a switching network, there are a number of sensor applications such as antenna arrays for which very fast analog multiplexing is required for many inputs. Semiconductor systems can be greatly enhanced and realistically supported with HTS switches at the interface.

The overall advantages of the HTS approach to semiconductor-superconductor systems are higher combined performance and unique solutions.

It will be the goal of this effort to assess the performance improvements of hybrid semiconductor-superconductor systems. Superconducting signal and power transmission lines at the chip and board levels will be modeled to determine the effect of interconnects on system performance. When desired parameters have been determined, e.g., line width, dielectric constant and impedance, test structures will be fabricated and tested.

Analysis will be made of the systems where optimum performance can be obtained with hybrid technology, e.g., semiconductor switches with superconducting interconnects. Such systems will be modeled to determine where such situations exist.

If the results of this study are positive, a detailed materials investigation of the superconductor/semiconductor interfaces will be made to assure that compatability exits. A test vehicle, which will demonstrate hybrid performance, will be designed, simulated, fabricated, and tested.

Proposed Budget

HYBRID SEMICONDUCTOR-SUPERCONDUCTOR SYSTEMS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	0	0	0	0	1
6.2	3	3	2	0	0	8
6.3A	0	5	5	4	0	14
Total	4	8	7	4	0	23

3. mm Wave Receivers. In the progression from the centimeter wave region into the millimeter and submillimeter regions of the electromagnetic spectrum, the fundamental background noise tends to decrease. Unfortunately, it is also true that the noise performance of conventional electronics gets worse, thus imposing a serious problem for the systems designer. For example, high performance systems presently demand cooling in order to function adequately. Systems such as communications links, passive mm wave sensing arrays, phased array radars, antennas, and synthetic aperture radars stress available technology and in some cases are not realistic without major device improvement.

If the electrical performance and device performance which present metal superconductors demonstrate at lower temperatures can be achieved at higher temperatures, then a host of very significant improvements can be made. Among them are very low attenuation antenna/transmission line configurations, which will improve the noise figure of a receiver. In some instances, the size of a phased array can be considerably reduced. Very-low-noise amplifiers, whether semiconducting or superconducting, can be cooled for sensitivity improvement. Since, very often, these mm wave systems are meant to be wideband, i.e., $\sim$10 GHz, superconductive chirp transform processing and or very fast A/D conversion can be used to sort out the data of interest. If a superconductive mixer were employed in the receiver, not only would the noise level be enhanced, but the required local oscillator power would be reduced by at least three orders of

magnitude. This would greatly reduce the spurious emission and also possibly allow a larger number of receiver channels for the same size/power.

In some applications where power is at a premium, the dissipation load of the system could be sufficiently small to allow a cryogen to be used thereby minimizing the size and weight. Of course, the small heat load also makes very-low-power refrigeration an attractive alternative.

The overall advantages for HTS mm wave receivers are very-low quantum-limited noise, wide bandwidth, low electrical power, and very-high-performance digital capability.

The goal will be to demonstrate feasibility and performance enhancement of a mm wave receiver which uses HTS elements. An evaluation of the elements of a high performance receiver will be made; this will include such items as antenna elements, transmission lines, amplifiers, mixers, digitizers, filters. The performance improvements possible using superconducting and semiconducting components will be investigated. This evaluation will be done both by theoretical analysis and experimentally by use initially of presently available materials technology. These data will then be used to guide application of the new HTS materials to this important developmental area.

Proposed Budget

mm WAVE RECEIVERS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	2	1	1	0	0	4
6.2	4	2	1	0	0	7
6.3A	0	3	3	2	0	8
Total	6	6	5	2	0	19

4. Infrared Sensors. Present infrared sensors already require cooling in order to achieve good performance at long wave-lengths. Superconductive tunnel junctions may offer a much larger spectral bandwidth and additional sensitivity compared with the present semiconductor devices. Moreover, for large arrays of sensors, whether they are cooled or not, the functions of transforming the analog currents into digital format with adequate sampling rate and linearity for later processing are very demanding. It appears possible to use the very high speed of superconductive electronics in order to multiplex and digitally convert a number of much lower bandwidth analog signals. Since superconductive electronics can do this at exceptionally low electrical power, the resulting refrigerator and electronics power may be much less than for a conventional system. Of course, if the sensors must already be cooled, the extremely small added heat load for the superconducting electronics is of little consequence. For modest mission times, the heat load can be absorbed by a liquid or a solid cryogen with no need for a refrigerator.

Once the sensor data are in digital format, it is feasible to multiplex the information serially thereby transferring the data to the standard room temperature output with high efficiency.

The anticipated overall advantages of HTS infrared sensors and associated electronics are very low power, high performance digital capability, high sensitivity, and small size and weight.

The goal in this development is to determine the capability of HTS to enhance high performance infrared sensing systems. HTS devices will be evaluated as sensors in comparison with existing semiconductor devices. Moreover, superconductive processing components will be investigated and tested in conjunction with both semiconducting and superconducting sensors. These functions will include: multiplexers, A/D converters and shift registers. In addition, techniques for interfacing between the cryogenic system and the warmer environment, will be investigated.

In order to understand and characterize the materials requirements, selected critical test components may be fabricated and tested initially with available lower temperature materials.

Proposed Budget

INFRARED SENSORS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	2	1	1	0	0	4
6.2	3	2	2	0	0	7
6.3A	0	1	3	2	0	6
Total	5	4	6	2	0	17

5. Digital Systems (Logic). A number of properties of superconductive films and devices make them attractive for digital applications. The Josephson junction has been investigated extensively as a digital switch using the lower temperature superconducting materials, and circuits using them have demonstrated gate delays of several picoseconds while dissipating only several microwatts per gate. Such high speed and low power imply high potential for very compact, very-high-performance computational systems. The new HTS materials should permit similar high performance. The power dissipation may be slightly higher, but the speed may be several times faster and the drive capability may be increased as well.

It is well known that using matched transmission lines throughout a computing system produces the highest performance. Present superconductors, with low-loss, low-dispersion transmission lines between devices and chips, satisfy that requirement. If the new HTS materials can be developed to a similar level of performance, that advantage will be retained. Superconductive lines also provide an almost ideal power bus; there is no resistive drop on the power distribution lines. The energy gap, as a fundamental material property, can be used to provide power regulation locally, on chip. Finally, in an era when 10^7-10^9 devices are envisioned to configure a system, and when the drive currents in conventional semiconductor microelectronic circuits may lead to destructive electromigration effects, the superconducting approach looks especially attractive.

The zero resistance and cryogenic environment combined should virtually eliminate electromigration and should greatly enhance reliability.

Given the above characteristics the implications for digital electronics are remarkable. One can project the computing power of a Cray I contained in a cube, 3cm on a side, and dissipating 250 milliwatts. Included in this volume would be a small high-speed cache memory only, i.e., no mass memory. Using HTS materials cooled with neon or nitrogen, such a system would operate more than five days on a single liter of cryogen, or could be cooled with an efficient miniature refrigerator consuming less than 10 watts of unregulated power. Even more awesome is the possibility of performance which is ten times that of a CRAY I CPU in a cube, 6.5cm on a side, dissipating 5 watts. This would include a large cache memory. The <u>overall</u> power requirement would be dominated by the refrigerator, consuming several hundred watts of unregulated power. (The CRAY II, a more advanced model than the CRAY I, uses about 65KW of refrigeration plus the 150KW of mainframe power.)

In scenarios where weight, volume, and power are at a premium, there is no other technology that can produce such performance. For DoD compute-bound problems such as synthetic aperture radar, acoustic array processing, superconductive technology offers unique solutions.

The goal of this project is to demonstrate feasibility of a fully functional superconducting logic family with the following parameters:

Device switching time < 10 psec

Fully loaded logic delay (FI = FO = 3) $\leqq$ 50psec

Power dissipation/gate $\leqq 100 \mu$w/gate

Operating temperature > 27K

Complete superconducting logic families will be designed, sufficient to support a general purpose computing engine. Both latching and non-latching logic will be investigated. <u>The design will use present lower temperature superconducting materials initially</u>, and be extendable to HTS materials. Logic families will be simulated to determine operating parameters. After selection of the most promising one(s), short strings of gates will be fabricated and tested to verify performance. Selected functions, e.g., adders, multipliers, and shift registers, will be designed, simulated, fabricated, and tested.

Proposed Budget

DIGITAL SYSTEMS (LOGIC)

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	1	0	0	3
6.2	1	2	2	0	0	5
6.3A	0	1	2	1	0	4
Total	2	4	5	1	0	12

6. Digital Systems (Memories). The attractive features of superconductive devices which apply to logic systems can also be applied to superconductive memories. The high speed logic units must be interfaced closely in space with memory which is comparably fast in order not to degrade the system performance. Thus again, low power and high speed are required. The low-power feature is even more striking, because in the standby mode, where current is stored in a superconducting loop, there is no power dissipation. The memory is non-volatile as long as the temperature is kept below T_C. The availability of nearly lossless, dispersionless transmission lines allows the CPU system to maintain a fast system clock. Since a high computation rate usually demands a large memory, a hierarchy of memories can be used with fast superconducting ones nearest the logic units and slower semiconductor bulk memories at the next level, quite possibly also at cryogenic temperatures. Cooling of the semiconductor devices would also enhance their reliability.

It is the goal of this project to demonstrate feasibility of a superconducting RAM with the following parameters:

Access time $<$ 1nS

Size $\geq$ 4K bits

Power dissipation $\leq$ 10 w/cell

Operating temperature $>$ 27K

Memory cells for fast CACHE memory use will be designed to take advantage of the superconducting properties of available lower temperature superconducting materials, with extendability to HTS materials. All candidate cells will be simulated, and the best performer will be chosen. Small or partially populated arrays will be fabricated and tested to verify the simulation. A decoder for CACHE memory will be designed, simulated, fabricated and tested. When parameters for both the cell and decoder are within acceptable limits, a test vehicle will be designed, simulated, fabricated and tested. The CACHE test vehicle will contain 1K bits.

Proposed Budget

DIGITAL SYSTEMS (MEMORY)

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	1	0	0	3
6.2	2	3	2	0	0	7
6.3A	0	1	1	1	0	3
Total	3	5	4	1	0	13

7. Three-Terminal Devices. The basic superconductive device, the Josephson junction may be switched from its zero resistance state to the voltage state either by directly injecting a current into a junction, or applying a current to a separate control line which causes the junction to switch. Both of these solutions are presently very effective for different circuit designs and have been ingeniously used. However, because the devices do not presently have gain, the resulting impact is to demand careful fabrication control which limits yield. In addition, the present means of controlling the device does not provide the engineer with a unique input/output relationship i.e. unique "on-off" control of the junction current. For many applications, both analog and digital, "three-terminal" device behavior would greatly simplify, and therefore enhance, the use of superconductive active devices. For these reasons, it is important to search for a device which operates at switching speeds of $\leq$ 10psec, dissipates a power $\leq$ 100μw, and produces power gain.

The goal of this effort is to develop a practical logic family based on a true three-terminal superconducting device with high speed and low power dissipation. Numerous novel structures and mechanisms have been proposed as a basis for three terminal devices. These approaches will be further investigated with the added incentive of higher temperature operation. Selected structures will be simulated, fabricated, and tested to determine if any deliver the desired performance. In addition effort will

be directed toward conception of completely new approaches to the realization of useful three-terminal superconducting devices.

Proposed Budget

THREE TERMINAL DEVICES

$M

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	1	1	0	4
6.2	1	1	2	2	1	7
6.3A	0	0	0	0	1	1
Total	2	2	3	3	2	12

8. Systems Demonstration Vehicle. Superconductive technology, like all others, must be fit into a complex of parts which performs a useful function. It is not possible to assess its value or to demonstrate its feasibility for use without going beyond the device or component stage. The systems problems, such as interfacing with inputs and outputs, cooling, and performance, can only be addressed by designing a test vehicle of credible size and complexity, by building it and by testing it. One fully expects that some small scale parts or devices, for example magnetometers or power buses, may be available and applied early in the program. Since these may require very simple configurations, they do not explore adequately the remaining questions.

Accordingly, it is the goal of this effort to provide, using the device structures described above, a system level demonstration of a superconducting and/or hybrid technology operating above 27K. With all necessary components in-hand through the preceding efforts, a system level test vehicle will be designed, built and tested. A thorough evaluation will be made of the performance advantages that can be obtained from the superconducting or hybrid system versus projected non-superconducting systems.

Proposed Budget

SYSTEMS DEMONSTRATION VEHICLE

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	0	0	0	0	0	0
6.2	0	0	0	0	0	0
6.3A	0	0	2	12	25	39
Total	0	0	2	12	25	39

9. Refrigeration. Presently most of the work on HTS materials has centered on $YBa_2Cu_3O_x$ with a transition temperature of $\sim$90K. For most applications one would like to operate at 1/2 to 2/3 of T_c, which suggests that the cryogenic fluid of choice would be liquid neon with a boiling point of 27.2K. For other applications, liquid nitrogen at 77.3K would be adequate. In both cases the latent heat of vaporization is 50 times that of liquid helium which translates to 50 times longer hold time for the same heat load in open cycle systems and to much simpler, more efficient closed cycle refrigerators. In many DoD applications where volume, weight, and input power are severely restricted, this relaxation on the cooling requirement can make the difference between feasibility and non-feasibility in the applications described in the preceding sections. In space applications passive radiative coolers can be made to operate at 80K. As still higher temperature superconductors are developed thermoelectric coolers may be adequate for some applications.

It is the goal of this effort to develop refrigeration techniques so that advantage can be taken of the fact that the new HTS materials can be operated well above the previously required liquid helium temperatures. A careful evaluation of existing refrigerators and cryostats will be made to determine available capabilities in the 27 to 77K range. Where needed, refrigerators will be designed, built and characterized in order to maximize efficiency and reliability and to minimize size and weight.

Cooling capacities will range from 50mw for systems with a few active devices such as magnetometers to 5 watts for a large, all-superconductive processing system. A separate class of refrigerator with hundreds of watts cooling capacity will also be developed and characterized for use with hybrid systems where the semiconductor elements contribute a significant heat load. A study of existing helium cryostats will be made to determine what changes are needed to optimize them for use at higher temperatures. For space applications, radiative coolers will be designed, which will handle heat loads from 10 mwatts to 2 watts. Experimental verification of their performance will be demonstrated. As higher temperature superconductors become available the possible application of thermoelectric cooling will be evaluated.

Proposed Budget

REFRIGERATION

$M

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	0	0	0	0	1
6.2	2	2	1	0	0	5
6.3A	0	3	1	0	0	4
Total	3	5	2	0	0	10

Proposed Budget

SMALL-SCALE APPLICATIONS SUMMARY

	$M					
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	11	6	6	1	0	24
6.2	18	17	13	2	1	51
6.3A	0	17	18	22	26	83
Total	29	40	37	25	27	158

D. Large-Scale Applications and Demonstrations

Large-scale applications of superconductivity of concern to DoD involve three primary technologies: i) supermagnets of all sorts by themselves and as components of larger systems, ii) electromagnetic cavity resonators for RF systems, and iii) shields for magnetic and/or electromagnetic isolation. While these technologies are rather mature for the lower temperature superconducting materials (e.g., Nb-Ti for wires and Nb for cavities and shields) these technologies have not yet been mastered for the newer HTS mateials. Some (but not all) of the development problems seem severe at this time, and considerable ingenuity, insight, and diligence will be required to effect the transition from the brittle ceramic pellets to structures useful for large scale applications. Similar problems have been faced in the past in the development of fabrication procedures for the brittle A15 type superconductors, Nb_3Sn and V_3Ga, and rapid progress is expected with the new HTS materials. As mentioned earlier, DoD has already made significant progress in large-scale superconductivity development programs, e.g., electric ship propulsion, airborne pulsed power generators, and superconducting cavity resonator particle accelerators to name a few. This portion of the DSRD proposal presents a coordinated thrust, building on this past DoD experience and interest, to exploit the new HTS materials in an accelerated time frame. The driving force behind this thrust is the greatly reduced refrigeration requirements implicit in their use.

The superconducting materials of greatest technological interest are type II superconductors. For such a superconducting material to generate intense magnetic fields, it is imperative that it possess an intrinsically high upper critical field H_{c2} (the field above which superconductivity can survive only in a thin surface layer), and a large condensation energy (corresponding to a large thermodynamic critical magnetic field, H_c) which is related to the maximum amount of current the material can carry in the superconducting state. For cavity applications and for some shielding applications, a third field is important, viz., the lower critical field, H_{c1}, which is the field at which, under equilibrium conditions, magnetic flux first penetrates into the bulk of a type II superconductor. Under flux penetration conditions in an AC field, type II superconductors are dissipative, and hence are unsuitable for high-Q cavity resonator applications. However, there is some evidence that at sufficiently high frequencies (extreme non-equilibruim conditions) the onset of flux penetration does not take place until well above H_{c1}. The potential value of the new HTS materials in cavity resonator applications rests heavily on the resolution of this scientific question.

The new HTS materials appear to possess extremely high H_{c2} values (a value of over 100 Tesla has been reported) and relatively high H_c values (a value of 2 Tesla has been reported). These facts suggest that the intrinsic limits to the amount of

current that can be carried by the new superconducting materials are quite large. However, the new HTS materials have only modest H_{c1} values ($\lesssim$0.1T); hence, high-power applications of RF cavities may be more "far term." H_{c1} and H_c are also important parameters in shielding applications, but they do not limit the maximum shielded field.

As already emphasized the critical current density, J_c, is an extrinsic property of a bulk superconductor. It is controlled by microstructural characteristics of the material (voids, second phase, grain boundaries, etc.) which can be manipulated through appropriate material processing. These studies are in their infancy for the new HTS materials and must be pursued rapidly. Values of J_c over 10^5 A/cm^2 at 77K have been reported in zero applied magnetic field for $Y_1Ba_2Cu_3O_7$, but a large and discouraging anisotrophy was also reported. For most large-scale applications J_c must remain large in high magnetic fields, H. Accordingly, it is essential that J_c(H) be evaluated over [illegible] range of fields. Early reports show a rapid fall of [illegible] increase of H; hence, research to improve this pr[illegible] It will be important to ascertain the types [illegible] "defects" which enhance J_c(H) and which [illegible] Also, the role that crystalline [illegible] J_c(H) must be determined. [illegible] [illegible]e refrigeration costs [illegible] [illegible]o J_c(H), as therm[illegible] t[illegible]peratures [illegible]

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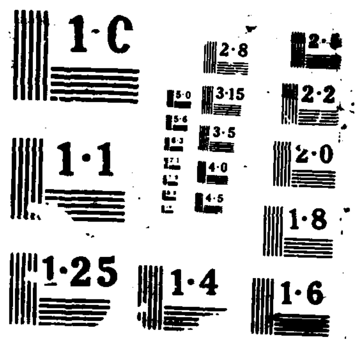
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will of course limit the maximum attainable fields of supermagnets operated at higher temperatures.

The rapid development of large scale applications of superconductivity depends critically upon careful integration of materials development/processing considerations and systems design considerations. The synergism of this approach will permit novel design concepts to be developed in concert with the evolution of the understanding and processing of the revolutionary new materials. The feasibilities of particular demonstration projects will depend, in large part, on progress achieved in early phases of the materials development and processing components of the program. In-house DoD scientific programs will be strongly coupled with industry at the outset so as to ensure that an industrial base is available for production when the development phase is completed.

Investigations of supermagnet structures will not be restricted to the standard wire-wound solenoid configurations most commonly used. Consideration will be given to novel structures such as the plate structure used in the high-field magnets at the National Magnet Laboratory and at the Naval Research Laboratory. This and other novel structures may be more amenable for magnetic field generation with the brittle HTS materials.

In some applications cavities and shields have a common materials base. In those instances it will be necessary to

produce dense materials with polished surfaces having minimal numbers of surface defects. Again a variety of fabrication techniques will be explored including bulk ceramic processing techniques, plasma sprayed coating techniques, and thin film deposition techniques.

From among the many important DoD large scale applications of superconductivity, several are summarized below together with indictions of where benefits can be derived by incorporation of the new HTS materials. Judgements are made as to whether an actual demonstration is near term, 1-3 years; mid-term, 3-5 years; or long term, >5 years. This is not a rating or ranking in terms of priority or mission impact and should not be so construed.

1. Shields (near term). Shields to confine or eliminate magnetic fields from specific regions in space are needed and often used in large scale applications of superconductivity. Shields are used on superconducting electric motors or generators to minimize stray fields from the nearby environment. Shields surrounding circuitry associated with sensitive electro-magnetic detectors (e.g., SQUID's) are used to suppress environmental noise. Shields are also of importance for magnetic field confinement and isolation in kinetic energy and directed energy weapon systems.

Shields can be made today with existing technology. Ceramic slip-casting, plasma spraying, etc., are all demonstrated techniques for making such structures. Testing of shield

characteristics and design concepts can and should begin immediately. For low-field applications, shielding ratios and field stability against both magnetic and thermal disturbances $H_{sh}(H, T)$ require testing. For high power applications, the maximum required shielding field, $H_{sh}(max)$, can be much larger than H_{c1} but will be signficantly smaller than H_{c2}. $H_{sh}(max)$, together with HTS material performance parameters, will determine the required shield geometry.

Once values for $H_{sh}(T, H)$ and $H_{sh}(max)$ are determined, system design can commence. Obvious near term demonstration areas are in existing superconducting systems, which already employ shielding. SQUID systems under development at NCSC and electric motors and generators under development at DTNSRDC are obvious candidates. Both on-going development projects have prototype systems in which existing shields could be replaced with the new HTS shields with attendant gains in performance and/or economy.

Cost of this program would be approximately $4M for materials R&D and $8M for design and systems incorporation. The funding profile in the following table includes heavy up-front funding, reflecting the near term character of this activity.

Proposed Budget

SHIELDS

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
			$M			
6.1	2	1	0	0	0	3
6.2	1	2	1	0	0	4
6.3A	0	1	2	2	0	5
Total	3	4	3	2	0	12

2. Supermagnets for Microwave and Millimeter Wave Sources (near term). Development of high-power, high-resolution microwave and millimeter wave systems is of major DoD importance. In the gyrotron an electron beam interacts with a high magnetic field. The resulting electromagnetic radiation is tunable by variation of the magnetic field and can be chosen to coincide with an atmospheric propagation window. Operation at 35 (100) Gigahertz requires a magnetic field of 1.3 (4.0) Tesla. Fields of the required geometries and magnitudes are typically supplied by superconducting magnets. Presently used supermagnets are fabricated from niobium-titanium and operate at 4.2K. The new HTS materials offer the possibility of operation at significantly higher temperatures (perhaps as high as 77K) with consequent convenience and economy in refrigeration.

Materials development efforts in support of this application will concentrate on conductors and structures matched specifically to microwave and millimeter wave tubes already in existence and will allow pesistent-current-mode operation. The required magnets are of modest size and of modest field strength, and system design considerations are relatively mature, and so early payoff can be anticipated.

Cost of the effort would be $5M for materials R&D and $5M for magnet development, distributed as shown in the following table.

Proposed Budget

SUPERMAGNETS FOR MICROWAVE AND MILLIMETER WAVE SOURCES

	$M					
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	1	0	0	3
6.2	0	1	1	1	0	3
6.3A	0	0	1	2	1	4
Total	1	2	3	3	1	10

3. <u>Supermagnets for Electric Ship Propulsion Systems (mid & far term)</u>. Since the early 1970s DoD(N) has been engaged in development of rotating electric machines as alternatives to the large reduction gears used to transfer the high-RPM power from a gas turbine to the low-RPM power required to turn a ship's propellor. Under this program superconducting motors and generators were developed, were installed in a ship, Jupiter II, and were successfully tested on the Cheasapeake Bay. Advantages of superconducting electric propulsion include weight reduction, reduced noise, flexibility in ship design, and increased fuel efficiency. A 40,000 HP superconducting motor would offer a savings of a factor of 4 in weight and a factor of 3 in diameter when compared to a conventional 40,000 HP air cooled motor. Still greater savings may be possible with the new HTS materials, for which refrigeration becomes more efficient, more reliable, and more convenient.

The initial thrust of this program will be to develop HTS field magnets suitable for replacement of the lower temperature superconducting magnets in existing developmental electric ship drive rotating machinery. As greater expertise is gained with the new HTS materials, entirely new high-performance designs will be possible. Some of these designs might incorporate active and/or passive superconducting shielding of the type to be developed as described in the section on shields above.

As very-large-scale HTS magnets become feasible attention will be directed to the development of magnetohydrodynamic thruster designs wherein the Lorentz force, developed by passing current through sea water in the presence of a magnetic field, propels the ship without need for a propeller.

The cost of this program would be approximately $10M for materials development and $11M for magnet development, distributed as shown in the following table.

Proposed Budget

SUPERMAGNETS FOR ELECTRIC SHIP PROPULSION SYSTEMS

	$M					
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	2	1	1	0	0	4
6.2	2	2	2	2	1	9
6.3A	0	1	2	3	2	8
Total	4	4	5	5	3	21

4. Superconducting Magnetic Energy Storage (SMES) (mid term). The concept of large-scale SMES was seriously proposed in the early 1970s and has received considerable support from DoE and EPRI, primarily for design studies. SMES systems have significant DoD implications as well. The concept of SMES is simply that energy fed into a superconducting inductor at low power levels over an extended period of time can be stored indefinitely and then can be withdrawn as needed, either slowly or rapidly. This approach to electrical power management is of potential use for ground-based systems, space-based systems, and military vehicle applications. Some concerns with SMES systems center on factors related to the input and extraction of power, but significant progress has already been made in this area.

DoD applications of SMES will include smaller systems than those envisioned for public electric utility applications and could utilize quite novel structural designs not possible for large domestic systems. These would include concentric and toroidal structures which have internally high magnetic fields but appear externally neutral.

Development of military SMES systems will doubtless require conductors specifically tailored for each application, and so this effort places heavy emphasis on identification of potential applications at an early stage. Of early interest are possible pulsed power applications for directed energy weapons.

Funding for an SMES program would be \$6M for materials development and \$7M for system development, distributed as indicated in the following table.

Proposed Budget

SUPERCONDUCTING MAGNETIC ENERGY STORAGE

$M

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	1	1	1	5
6.2	0	0	1	1	2	4
6.3A	0	0	0	2	2	4
Total	1	1	2	4	5	13

5. Electromagnetic Launchers (mid term). In 1978 a DoD effort was initiated to assess and advance the state of electromagnetic propulsion technology. This effort is focused and overseen by DARPA and has been quite successful. The concept of an electromagnetic launcher is that terminal velocities of the projectile are not limited by an exploding gas but by the velocity of a traveling electromagnetic pulse. Generation of this pulse involves a prime generator (possible superconducting homopolar generator), a storage device (possible SMES), several opening and closing switches (possible superconducting switches), rails (or phased pulsed supermagnets), and a projectile. Potential applications of the new superconducting materials are obvious.

Electromagnetic launchers can be used in weapon systems, launching systems (space), and impact fusion. Thus they have wide ranging potential application but need further development. the advantages offered by the new HTS materials may significantly help this development.

In addition to a materials development program for electromagnetic launch applications, this effort would include a strong superconducting film component with potential switch application. Such a program already exists in the DoD, and performance parameters look marginally acceptable with conventional superconducting materials, and so HTS could have a major impact.

Funding for this program would be $8M for materials development and $11M for design assessment distributed as shown in the following table.

Proposed Budget

ELECTROMAGNETIC LAUNCHERS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	2	2	1	7
6.2	0	1	2	2	1	6
6.3A	0	0	1	2	3	6
Total	1	2	5	6	5	19

6. Directed Energy Weapons (DEW) (mid term). Achievement of directed energy weapons for space deployment will be greatly assisted by the development of lighter-weight, lower-loss resonant cavity accelerators as well as suitable magnetic shields. Although the electrical losses in HTS materials are not zero at accelerator frequencies, they are much lower than that of normal metal cavities. Development of superconducting cavities using niobium has proven successful for accelerating electrons. Many of the material and design problems are known. The reduced cost, greater reliability, and reduced complexity of operating at higher temperatures make development of the HTS materials very desirable.

Materials problems to be faced here are different from conductor and field generating structure problems. For cavity applications it is essential that theoretical material density be achieved with defect free surfaces. Processing techniques to produce these structures will be similar to those used to fabricate electromagnetic shields, but much more severe. Cavities can be fabricated by ceramic processing techniques; hence, medium term payoff is expected. This development would require \$6M for materials development and \$8M for design development, distributed as shown in the following table.

Proposed Budget

DIRECTED ENERGY WEAPONS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	1	0	0	3
6.2	0	1	2	2	1	6
6.3A	0	0	1	2	2	5
Total	1	2	4	4	3	14

7. Magnetic Bearings (mid term). Bearings are important components for any rotating or translating system. Replacement of worn-out or damaged bearings is a major military cost item. When two materials slide or roll over one another damage is inevitable even with top quality lubrication. Also, bearing noise is a consideration in the development of quiet submarines.

Noncontact "magnetic bearings" can be developed to alleviate these problems. A radial field will generate eddy currents in a conducting, rotating shaft which will produce a repelling force between the shaft and the shaft housing. Thus the shaft will be magnetically confined without any physical contact of the materials. Such bearings will be extremely valuable in applications requiring high shaft speeds or vibration free bearings, such as in cryocoolers.

Magnetic bearings require fields of modest magnitude in restricted spaces. Refrigeration approaches and specialty supermagnets must be developed for such restricted spaces. Because some progress has already been achieved, this is a medium term payoff application.

Cost of the program would be $5M for materials R&D and $6M for system design and tests, distributed as shown in the following table.

Proposed Budget

MAGNETIC BEARINGS

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	1	0	0	0	2
6.2	0	1	1	1	1	4
6.3A	0	0	1	2	2	5
Total	1	2	2	3	3	11

8. Mine Sweeping Supermagnets (mid term). Exploding mines magnetically is a concept which has been frequently envisioned as a use for high-field magnets. A large intense field magnet, reinforced against shock, and suspended from a moving platform is needed. Cost of operating such a large superconducting system would be greatly reduced by operation at 77K vs 4.2K. This factor alone moves the application from far to medium term.

Cost of the program would be $5M for materials R&D and $7M for design studies and tests, distributed as shown in the following table.

Proposed Budget

MINE SWEEPING SUPERMAGNETS

			$M			
Budget Category	FY88	FY89	FY90	FY92	FY92	Total
6.1	1	1	1	0	0	3
6.2	0	2	2	0	0	4
6.3A	0	1	2	2	0	5
Total	1	4	5	2	0	12

9. Pulsed Power Systems (far term). The Air Force has devoted major effort to development of superconducting magnets for airborne pulsed power generators. This program has achieved significant advances in developing both the superconducting conductors for use in the magnets as well as the insulation on the conductors, which becomes critical in such applications. The parameters for pulsed magnet systems are different from those typical of DC systems. In a pulsed mode, the superconducting magnet is not lossless, and considerable effort must be devoted to minimizing these losses and providing refrigeration to compensate for them. This means fully "stabilized" wires with very-small-diameter superconducting filaments. Operation at higher temperatures by incorporation of the new HTS materials can greatly improve the cryogenic stability, because the heat capacity is so much greater at higher temperatures. The requirement of small diameter filaments in a stabilized wire make this problem challenging and one of specific military importance, but of longer term payoff potential.

This program will concentrate on developing composite conductors of appropriate design to be useful for pulsed application. It will also include research on insulation, which is of particular concern to this project. Design features of the program include an assessment of the cryogenic refrigeration requirements and incorporation of refrigeration and structural considerations in a systems approach.

This program would require about \$10M for materials development and \$7M for design development, distributed as shown in the following table.

Proposed Budget

PULSED POWER SYSTEMS

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
			$M			
6.1	2	2	1	1	0	6
6.2	0	0	3	2	1	6
6.3A	0	0	0	2	3	5
Total	2	2	4	5	4	17

10. ELF Communication (far term). Extremely low frequency communication via magnetic wave has been proposed as a means of communication with submerged submarines. The signal detector would be a SQUID magnetometer while the signal generator would be a rotatable superconducting magnet. Very low frequency modulation of the rotating magnet would provide a low data-bit link to the submarine. This type of communication would be used in a go-no go scenario.

Because a large-moment superconducting magnet is needed -- preferably operating in a persistent mode -- the reduced refrigeration cost of operation with HTS represents a significant change in the economics. Engineering problems associated with rotating and modulating a large structure, while maintaining a cryogenic environment must be carefully worked out. Thus, this project is long term. Funding would be $7M for materials R&D and $12M for design and tests, distributed as shown in the following table.

Proposed Budget

ELF COMMUNICATION

$M

Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	1	2	2	1	0	6
6.2	0	1	3	2	1	7
6.3	0	0	0	3	3	6
Total	1	3	5	6	4	19

Proposed Budget

LARGE-SCALE APPLICATIONS SUMMARY

			$M			
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	13	12	10	5	2	42
6.2	3	11	18	13	8	53
6.3A	0	3	10	22	18	53
Total	16	26	38	40	28	148

11. Other Applications. There are several other large-scale applications of superconductivity, of importance to DoD, which should also be considered, but which are not discussed in detail here. Most involve large magnetic fields, and hence would draw heavily on materials development aspects of applications already discussed above. At all stages of DSRD program progress, assessments and evaluations of large scale applications will be continued to guide choices of demonstration vehicles which show greatest prospects for meaningful impact. Other applications of possible interest include: free electron laser (magnets for wigglers), synchrotron radiation sources (magnets for the bending fields), magnetohydrodynamic energy sources (magnets), nondestructive testing, and ore or materials separation (magnetic field gradients).

VI. DSRD BUDGET RECOMMENDATIONS

The scientific and technical work units outlined in the DSRD program plan represent a very aggressive approach. This is evident in the estimated budget requirements for individual program blocks, which have already been presented. It is also evident when those individual budget estimates are combined to yield the total budget estimates as set forth on the last two pages of this report. Although the individual elements of this budget are subject to considerable uncertainty it is believed that the total represents a reasonable estimate of the amount of funding which will be required to bring HTS to a state of maturity

suitable for incorporation in a variety of military-systems-specific advanced development projects.

For a number of reasons this budget figure will require adjustment. Some of the R&D results sought in the DSRD program plan may become generally available as a result of investigations by other agencies, by industry, or even by other countries. Also, some of the proposed projects are of relatively high risk, and so some are unlikely to be carried to completion. Moreover, additional scrutiny of some of the identified projects could reveal too little ultimate payoff to justify their being aggressively pursued. On the other hand, some very-high-payoff projects may encounter obstacles which dictate higher funding levels than originally planned. Also, as HTS technology matures, entirely new opportunities will surely emerge and will merit funding. All factors considered, the DSRD budget estimate presented here should be regarded as a first iteration, subject to adjustment as HTS technology is advanced.

AGGRESSIVE TECHNOLOGY-LIMITED BUDGET FOR DSRD PROGRAM

	$M					
Budget Category	FY88	FY89	FY90	FY91	FY92	Total
6.1	40	40	31	19	12	142
6.2	28	46	54	38	30	196
6.3A	0	22	32	56	58	168
Total	68	108	117	113	100	506

123

AGGRESSIVE TECHNOLOGY-LIMITED BUDGET FOR DSRD PROGRAM

	$M					
	FY88	FY89	FY90	FY91	FY92	Total
Characterization/Search	10	16	15	16	14	71
Processing	13	26	27	32	31	129
Small-Scale	29	40	37	25	27	158
Large-Scale	16	26	38	40	28	148
Total	68	108	117	113	100	506

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